The multidisciplinary influence of common sustainability indices

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Sustainability is often poorly defined and difficult to measure. We describe several concepts from ecology, economics, and physics, that have contributed to sustainability indices, and discuss their positive and negative aspects. Indices range from mostly ecological (such as ecosystem resilience and global human carrying capacity), to those inspired by both economics and ecology (green income and maximum sustainable yield), to a mix of ecology and physics (exergy and emergy). Economic concepts such as substitutability of natural and human capital (the "weak" versus "strong" sustainability debate), and throughput of natural resources through an economic system, are the basis for several strictly economic indices. The second law of thermodynamics, which dictates the decrease in usable energy, has also had an increasing influence on sustainability discussions. The indices described here address different aspects of the interactions between human societies and ecosystems, and are therefore probably most effective when used in combination.

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Despite its use as a target for policy decisions, sustainability and its many permutations (sustainable use, sustainable growth, sustainable development) remain conceptually vague (Goodland and Daly 1996). Sustainability is usually used to refer to a distribution of resources that is equitable, between all humans living now and among present and future generations, and use of these resources so as not to jeopardize the continued persistence of the planet's biodiversity and ecosystems (National Research Council 1999; Raven 2002). In some cases, definitions of sustainability can contradict each other, especially those of different professional disciplines (Goodland and Daly 1996). Although a sustainability concept is a seemingly rational guide to creating a long-term, positive relationship between humanity and the planet, murky and conflicting definitions hamper our ability to determine whether this relationship has been achieved.

Sustainability indices inspired by traditional ecological and economic theory tend to focus on the degree of damage that ecosystems can withstand. The two disciplines differ in the conceptualization and scope of the issue. Some sustainability concepts view human societies as part of the system and blend both economic and ecological theory, thereby eliminating the polemic. Others have turned to physics and the principles of thermodynamics for a common currency with which to quantify sustainability across disciplines. In this article, we examine several ecological, economic, and physics concepts and the sustainability indices they have generated. We emphasize indices that are grounded in fundamental principles and that include a measurable target or goal to indicate when sustainability has been reached or maintained. We do not cover the many statistics (from all disciplines) that have been used to conduct sustainability assessments of cities and countries (Molden and Billharz 1997). Although some of the indices discussed here encompass ideas from disciplines other than ecology, economics, or physics, these are not covered in this review.

In a nutshell:

- The concept of sustainability has been addressed by a wide range of disciplines
- Many quantifiable sustainability measures have been developed from the perspectives of ecology, economics, and physics
- No one sustainability index is likely to capture all of the types of interactions between humans and the environment, so sustainability measures are probably best used in combination

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Sustainability concepts: ecological

Resilience

Although the word "resilience" has been used somewhat interchangeably with stability, persistence, and resistance, the term usually refers to the time required for a system to return to a particular dynamic regime after a perturbation, or to the amount of perturbation that a system can absorb before shifting to an alternate dynamic regime (Holling 1973; Grimm and Wissel 1997). Resilience is created through feedback loops in ecosys-





Figure 1. *Urbanization of the Mill Creek watershed, upon which the city of Cincinnati, Ohio, was built, has reduced the watershed's ability to provide regeneration of groundwater stores, as the concrete channelization of the tributaries prevents water infiltration. (a) Although removal of concrete channels and riparian restoration to a more natural regime may be possible for some stretches of the Mill Creek, (b) restoration of other stretches is almost impossible due to development right up to the river's banks.*

tems that increase their self-regulating capacity (Chapin *et al.* 1996). This has led to the hypothesis that ecosystems evolve to maximize resilience within environmental constraints (Cropp and Gabric 2002). Resilience, as applied to sustainability, focuses on the degree to which human activities increase or decrease the resilience of a particular dynamic regime that provides desirable ecosystem goods and services. This concept emphasizes the dynamic nature of ecosystems, instead of regarding them as static and able to provide a fixed amount of natural resource continuously. Since many undesirable ecosystem regimes can be highly resilient, sustainability further implies a focus on those regimes that are not only resilient, but also most beneficial to humans (Carpenter *et al.* 2001; Jackson *et al.* 2001; Orr 2002). Restoration of an ecosystem to a particular desirable regime is also an important sustainability goal, although restoration may not be an option past a certain threshold of ecological damage (Figure 1).

Carrying capacity

Several sustainability indicators estimate humanity's total appropriation of the resource stocks and flows provided by ecosystems in relation to the remaining resources needed by ecosystems for stability and regeneration (Rees 2002). Once applied only in reference to nonhuman species, the ecological term "carrying capacity" has also been used to measure the pressure a human society exerts on an ecosystem (Arrow *et al.* 1995; but see Price 1999). Wackernagel and Rees (1997) call this concept a society's "ecological footprint", and Wackernagel *et al.* (2002) estimated that, by 1999, humans were using up to 120% of global capacity. The implication is that a sustainable use of global capacity would be at or below 100%. The ecological footprint can also be expressed in terms of how many planets would be required to support the current global human population if all individuals lived at a particular standard of living (Rees 2002).

Maximum sustainable yield

For economic sectors that process renewable natural resources, such as the logging and fishing industries, the maximum sustainable yield (MSY) and similar indices have received a great deal of attention and use (Clark 1990). The MSY index is an offshoot of the carrying capacity concept and is calculated from the growth function of the resource, specifically as the growth rate changes with the stock (or population size) of the resource. Broad sustainability occurs when all resources are harvested at sustainable rates. Resource extraction or harvest occurs at a rate such that the amount of resources removed equals the amount produced by the ecosystem, much like withdrawing only the interest from an account and leaving the principal unchanged to generate more interest. While the MSY measure may seem simple in theory, in practice, miscalculations and inadequate attention to ecosystem dynamics can lead to collapse of the resource (Zabel *et al.* 2003).

IPAT

Recognizing that affluence and technology can influence the per-capita resource use by human societies, Ehrlich and Holdren (1971) adapted the carrying capacity concept into an "IPAT" equation (where I = impact, P = population size, A = affluence, and T = technology) that accounts for economic activity. The IPAT index recognizes that not only population growth, but the per-capita resources used by that population (affluence), and technological influence on resource use per good produced (production efficiency; Waggoner and Ausubel 2002), are important factors of the overall level of impact

Table 1. Positive and negative aspects of some common sustainability indices

Concept	Metric	Positive aspects	Negative aspects
Resilience	Intensity of disturbance required to move system to a new regime	Incorporates ecological uncertainty and variability into measurements	Identification of regime boundaries (which are not fixed) difficult, existence of undesirable regimes discovered post hoc
Carrying capacity	• "Ecological footprint" • MSY • IPAT	Focus on human resource use; data on resource use usually available	Rates at which ecosystems supply resources not well understood
Income	• "green" NNP	Includes natural capital in income and productivity accounting; consideration given to natural capital	Depreciation of natural capital relies on accurate valuation of ecosystem goods and services
Steady-state economy	Stocks of natural resources kept constant, rate of stock used matched to rate of supply available	Focus on human resource use; data on resource use usually available	Stocks of natural resources not static; some difficult to measure. Miscalculations can lead to over-exploitation
Thermodynamics accounting	• Emergy • Exergy • Ascendency	Can convert many different resource flows into one unit; assess sustainability of systems at multiple scales	Must have detailed data for imports, exports, and energy requirements; may be prohibitive for large systems

exacted on the environment. This equation, and others like it, are used to determine whether the impact of a human society is increasing or decreasing over time, and to compare impacts between societies of different population sizes or affluence levels (Haberl and Krausmann 2001; Waggoner and Ausubel 2002; Liu *et al.* 2003). On its own, however, the measure can be misleading if the environmental impacts of affluence are exported to other societies (Goodland and Daly 1996; Fischer-Kowalski and Amann 2001).

■ Sustainability concepts: economics

"Weak" versus "strong" sustainability

The substitutability of man-made capital and natural capital is at the heart of most purely economic concepts of sustainability (Figure 2). In the absence of technological innovation, if a non-renewable resource cannot be substituted with man-made capital, sustainability is impossible (Dasgupta and Heal 1979). "Weak sustainability" assumes a high degree of substitutability between man-made and natural capital, while "strong sustainability" assumes that man-made and natural capital are complimentary in production (ie cannot be substituted for one another; Pearce 2002). This dichotomy is important when considering the opportunities available to a future, as yet imaginary, generation of people facing an uncertain array of options between man-made and natural capital. Strong sustainability proponents believe that policies based on a weak sustainability situation will cause the exhaustion or extinction of non-substitutable resources, reducing the choices that can be made by future generations. Weak sustainability proponents argue that the precept of strong sustainability shackles future generations to the current generation's value judgments (eg Solow 1999).

The existence of uncertainty is, of course, the reason there is discrepancy in opinion about future options. The current generation cannot know what will or will not be substitutable in the future, nor can the current generation know with certainty the potential nonlinear relationships and threshold effects in populations or natural conditions. Castle *et al.* (1996) propose a third alternative that explicitly takes into account uncertainty. Building on the concept of the "safe minimum standard", these authors maintain that economics is a discipline best used for analysis of subsystem sustainability (noting that forestry, fishery, and mining are economic by definition). Under uncertainty, minimizing the cost of maintaining flexibility is paramount. In fact, the authors assert that instead of searching for the rare and localized practices in extractive industries that are sustainable, economists' efforts would be better spent on understanding common, widespread practices and developing institutional mechanisms that encourage more flexibility.

Net National Product

Net National Product (NNP), or national income, equals the total incomes of the people in an economy, after accounting for capital consumption or depreciation. NNP can be modified to account for depreciation of natural resource capital, and therefore better represents a measure of conservation than more commonly cited economic measures such as Gross National Product (GNP) (Weitzman 1976; Hartwick 1990; Maler 1991). As currently calculated, GNP does not distinguish between those economic activities that reduce natural capital,

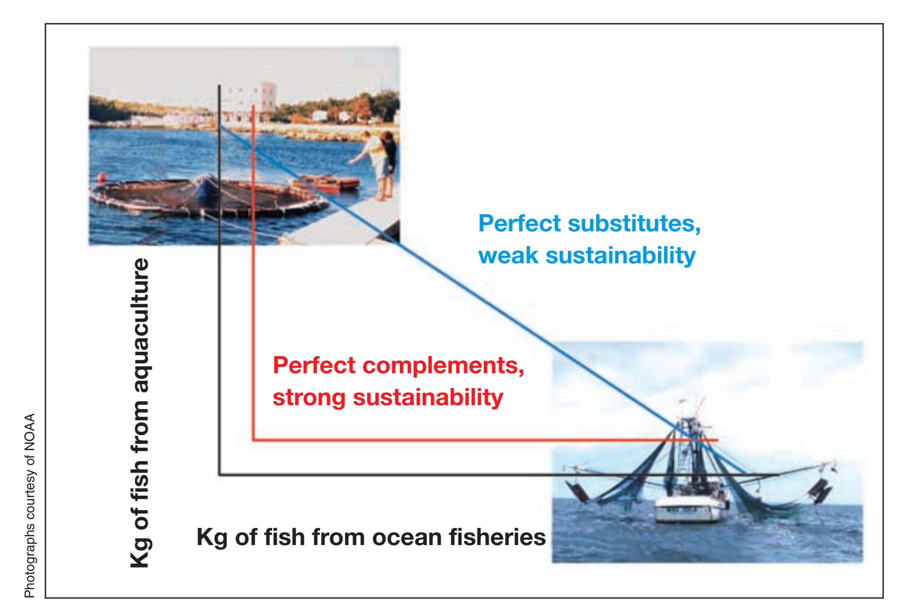


Figure 2. *An example of "weak" versus "strong" sustainability. The dichotomy between ocean fisheries and aquaculture (fish farms) illustrates weak versus strong sustainability. Two lines (or isoquants) indicate a total amount of fish available for consumption. An increase in the available amount of fish is indicated as an isoquant moves diagonally away from the origin, while the shape of the isoquant indicates the degree of substitutability between the two resources.*

such as clear-cutting, and those that do not. In this way, GNP can provide a misleading measure of the sustainability of a country's economy.

Accurate measurement of natural capital depreciation is essential to calculating a meaningful "green" NNP (Asheim 1994; Pearce 2002). While man-made capital and its depreciation are relatively easy to value, the valuation of change in a natural resource, or other capital not traded in the market, is problematic. Non-market valuation techniques (such as contingent valuation, hedonic valuation, etc) are commonly used to assign prices to these extra-market goods, such as ecosystem services, but these techniques are relatively new, so adequate checks for accuracy have not been fully developed (Costanza *et al*. 1997; Bockstael *et al*. 2000). There is also considerable debate over whether the entire present and future value of services critical for life can even be measured (Heal 2000). However, even under strict assumptions of perfect price information for all market and non-market goods, NNP may not be a general indicator of sustainability (Asheim 1994). This is due to the differing utility and discount rates people assign to different types of capital. Furthermore, Norgaard and Howarth (1991), among others, note that while use of non-market valuation to internalize externalities might bring about efficient *intra*-generational allocations, *inter*-generational transfers should not be evaluated by efficiency criteria alone.

Steady-state

Economic thought inspired by ecological insight has prompted some economists to argue against economies that exhibit continuous growth, advocating instead for a "steady state" economy (Daly 1987). This duality is best known as the "cowboy" versus the "spaceman" economy (Boulding 1966). In the former, the cowboy consumes and befouls the frontiers of an "open" system with reckless abandon, knowing that there will always be adequate resources further west. The spaceman, operating within a closed system, adopts constraint with his resources and increases quality, not quantity, of output. Sustainability indices that derive from the latter view focus on the level of throughput of natural resources through an industrial sector or economy, emphasizing the quality of the end product, the impact of the products (including byproducts) released back into the environment, or the social welfare gain from a particular level of throughput (Femia *et al*. 2001; Kaivo-oja *et al*. 2001).

Sustainability concepts: physics

The second law of thermodynamics states that a system closed to mass and isolated from external sources of energy tends toward higher entropy, meaning that gradients of mass, energy, chemical concentrations, and so on, that are present in the system degrade over time. Such gradients provide the identifiable "organization" or structure of the system and make available useful energy, termed "exergy", for work. While ecosystems and human economies are ultimately beholden to the second law, these systems can use external energy, such as that of our sun, to maintain and even increase local gradients. Indeed, Kay and Schneider (1992) have suggested that living systems have evolved precisely to degrade solar energy. Thermodynamic-based principles governing the development of ecosystems include the maximization of the flow of "emergy" (Odum 1996), the maximization of exergy storage (Jørgensen and Mejer 1981), and the maximization of "ascendancy" (Ulanowicz 1997). While not sustainability indices in and of themselves, emergy, exergy, and ascendency are attractive because of their potential to compare disparate stocks and flows, providing a common currency with which to analyze both economic and ecological systems.

Emergy

Emergy is the amount of energy that has gone into, or is embodied in, a particular product or service. Recognizing the importance of ecosystem inputs to human activity, the concept of emergy has been used to develop methods of accounting for systems, including ecosystems and human economies (Odum 1996). A sustainable system would have a net positive (or zero) emergy flow across its

boundary (Campbell 1998; Giampietro and Mayumi 2000; Brown and Ulgiati 2001). However, this approach does not directly take into account emissions impacts on the environment that result from the production of a product, and the use of life cycle impact assessment techniques may therefore be appropriate (Hofstetter 1998).

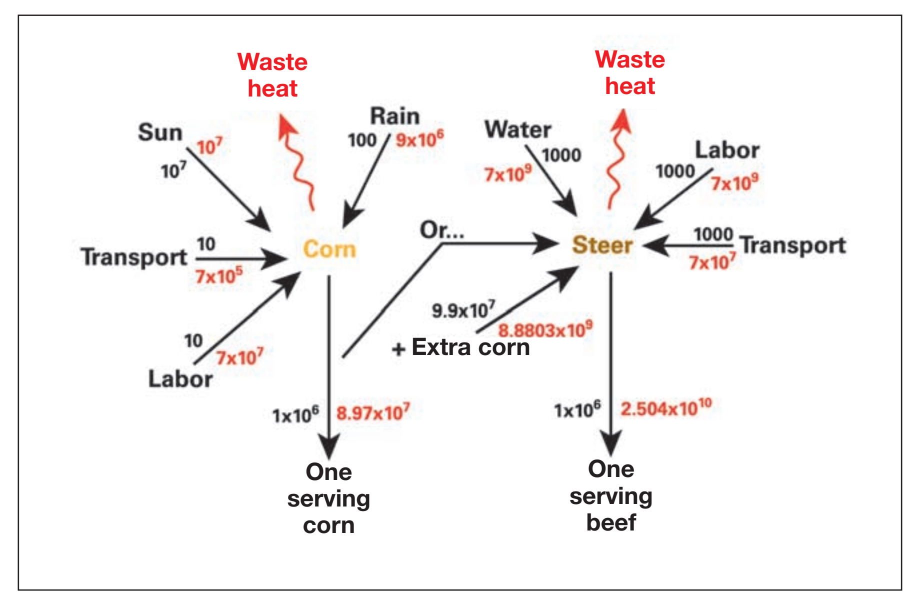


Figure 3. *Hypothetical exergy (black) and emergy (red) flows involved in the production of one serving ($1x10^6$ joules) of corn versus one of beef. Exergy is the amount of available energy for work. Emergy tracks all energy embodied or used in making the product, in terms of an equivalent unit of solar energy. One can either eat the corn directly, or (with supplemental corn) feed it to a beef steer and eat the beef. The ratio of emergy to exergy (not shown) gives the amount of available energy from the sun (solar exergy) necessary to produce an amount of product with one joule of available energy (exergy). In this case, about 89.7 joules of solar exergy are required to produce one joule in the form of corn, while 25 040 joules of solar exergy are required for one joule in the form of beef. The production of that same serving of corn releases about $9x10^6$ joules as waste heat back into the environment, while the serving of beef releases $99x10^6$ joules as waste heat.*

Exergy and ascendency

Szargut *et al.* (1988) have suggested that the exergy content of waste relative to that of the environment may be related to its potential to do harm, but this has not been explored extensively. Bastianoni (1998) equates pollution to an exergy loss in an ecosystem in response to an increase in the emergy of an input flow. However, such an approach requires that impact assessment be made in terms of exergy losses. Jørgensen (1995) has combined the concepts of exergy and buffer capacity into an index of ecosystem "health", based in part on the resilience concept. Ascendency is a measure of the diversity and degree of connectivity in a system (Ulanowicz 1997). Cropp and Gabric (2002) examine the dynamics of a simple model under different parameterizations. They found that parameters that maximize resilience also maximize metrics based on power, exergy, and ascendency. However, while quite powerful from the point of view of energetics, these measures and others based on thermodynamics do not directly account for the economic component of sustainability. Figure 3 illustrates a hypothetical calculation that uses emergy and exergy to compare the energetic efficiency of producing a serving of corn versus a serving of beef. Here, total environmental investment (in terms of emergy) is less for corn than for beef. Plants represent a more efficient food source, as much less exergy is used to maintain their metabolism compared to animals, particularly warm-blooded mammals. However, inputs such as fossil fuels, pesticides, and herbicides for corn production would decrease this relative efficiency.

■ Hypothetical integration: fish protein harvesting

Sustainability is a multidisciplinary issue, and assessments of sustainability must incorporate knowledge and insights from multiple disciplines (McMichael *et al.* 2003). Since no one index is likely to be a "catch all", a combination of indices that cover ecological, economic, and physical concepts is more likely to provide an accurate assessment of the sustainability of our activities. Although the integration of these multidisciplinary perspectives (along with other disciplines not discussed here) is critical to a truly sustainable interaction between human societies and their environments, this integration is difficult and therefore rarely undertaken. Here, we use the hypothetical issue of harvesting fish protein (from both oceanic and aquaculture sources) to demonstrate one approach to this integration (Figure 2).

Ecological approach

An ecologist could approach the issue of sustainable harvesting using the resilience and carrying capacity concepts. Ecologically, this would not only ensure species persistence, but also preserve ecosystem resilience. For ocean harvests, ecologists could determine the size of the disturbance (number, sex, and age class of fish removed for each species) that ocean ecosystems could withstand without triggering a shift to a different ecosystem regime (especially if that regime was less desirable from a fisheries standpoint). For aquaculture production of fish protein, ecologists could again determine the size of the disturbance that the surrounding ecosystems could

withstand without risk of a regime shift. In this case, the disturbance would be pollution by nitrogenous waste and potential risk to the gene pool of nearby native fish populations as a result of escapes.

With that knowledge in place (ignoring the real-world difficulty of gaining this information), ecologists could then determine the maximum amount of fish protein to be sustainably produced by aquaculture. Ocean-caught protein could then be treated as an extra resource, above and beyond what is available from aquaculture, and the available amount would fluctuate from year to year. The wild species available to be harvested (MSY) would also fluctuate as a result of the populations' response to previous fishing pressure as well as the species' dynamic interactions with other species and the weather. However, the above assumes that the food source for the aquaculture fish is constant. In reality, the food base for aquaculture usually originates from the ocean, so the amount of fish that could be produced sustainably from aquaculture will fluctuate with changes in ocean food webs. From an ecological perspective, the dynamics of the ocean ecosystems should set the annual limit of fish protein available for human consumption.

Economics approach

Economists would focus on the degree to which aquaculture and ocean-harvested fish are substitutable in the market. According to the weak sustainability view, aquaculture fish are substitutable for ocean-caught fish. This view assumes, among other things, no difference in pollution or other negative effects of using either source, and requires that either there is no difference between the kinds of fish species provided by either source, or that the species of fish does not matter to consumers. Weak sustainability also assumes that the total amount of fish could be supplied solely by aquaculture, or by the oceans, or some mix of the two. Assuming perfect substitutability, if wild fish species become extinct, the level of human consumption can still be maintained through aquaculture.

According to strong sustainability proponents, consumers do have a preference for certain types of fish, and while all species can be harvested from nature, only a subset of those species can be raised through aquaculture. As both aquaculture and ocean fish sources are linked by a single food source for the fish (smaller fish and invertebrate species from the oceans), diverting a large proportion of the food source to aquaculture will reduce the stocks of wild fish.

Some argue that the pollution and disease vectors generated from aquaculture (particularly those that are directly connected to oceans) could threaten wild fish stocks and, if not substituted, would decrease the total amount of fish protein available to humans (ie the isoquant would move closer to the origin in Figure 2). If this is true, there are social costs that are not realized in the production decisions of the private aquaculturist. Economic policy might include the estimation of social costs associated with production by using nonmarket valuation techniques, and a tax would be imposed specifically to cause harvesters of the resource to take into account the social costs of their harvest, and make their harvest decisions appropriately. From the market's point of view, the substitutability between aquaculture fish and ocean fish is manifest in consumer preferences (demand) and in costs (supply). Quantity demanded might be affected by revelations about the ecological substitutability between the fish, while quantity supplied would be affected by scarcity and price controls.

Thermodynamics approach

From a thermodynamics perspective, the main interest is in the natural and human-mediated energetic processes that form and maintain the organization of the system in which the wild and aquaculture fisheries are embedded. However, it is not yet clear how measures such as exergy, emergy, or ascendancy can give insight into ecosystem function and response to stress. As a practical response, a calculation of energy balances can be performed. An emergy calculation would involve contributions from inputs such as feed, support goods and services (fuel, durable capital, etc), as well as the ecosystem and environment (sunlight, estuarian inflows, etc). These would be compared to the emergy content of the products through various indices to characterize in some sense the return on investment in terms of emergy (Brown and Ulgiati, 2001). Exergetic calculations would follow a similar procedure, although these are concerned with the energy content of immediate inputs rather than their cumulative energy as given by emergy. Exergetic calculations are typical of engineering analyses and can lead to improvements in production efficiency.

Thermodynamic approaches are not usually used to assess the direct environmental impacts of harvesting wild fish protein versus aquaculture. Instead, a life cycle impact assessment might be used to account for the impacts of various harvesting schemes on such impact categories as global warming potential, eutrophication potential, aquatic ecotoxicology, and so on (Hofstetter 1998). An active area of research is characterizing such impacts in terms of exergy losses or emergy inputs or both.

An integration

If the absolute amount of fish protein is established by ecological criteria, then the harvestable amount of protein from oceanic and aquaculture fish species will vary by year and by species. Within these broad constraints, a thermodynamic assessment could determine the relative energetic costs of the fish species harvested from either

source. Species that are energetically costly to harvest, but socially desirable, would be very expensive (driving down the quantity exchanged in the market), while less energetically costly fish species may become more accessible as a result of lower prices. Economic policy, influenced by the above assessments, would ensure that the price consumers pay for fish protein would be determined by the ecological and physical constraints of the fishing system.

Conclusions

Although the integration of sustainability measures from a variety of disciplines is necessary, none of the indices reviewed here have been rigorously tested for accuracy or effectiveness. This should be done prior to integration. Indices need to be measured against each other for the same society and tracked over time. Low correlations between indices may indicate that either some indices are deficient in the type of information they incorporate, or that some are measuring characteristics of the society ignored by the other indices. If the benchmarks for sustainability are sound (and this may be a big "if"), those indices that use the most relevant information to accurately track the path of the society and its relationship to these benchmarks would become apparent.

Regardless of testing, all of these indices will suffer from two unavoidable problems: insufficient data and uncertainty. Increased resources dedicated to data gathering would reduce but not eliminate this first problem. Perhaps unsurprisingly, it is the second problem that defines, and at the same time limits, our understanding of sustainability. Ecologically, a great deal of uncertainty surrounds the probability of human or natural disturbances that are sufficient to push critical ecosystems into as yet unobserved and highly undesirable regimes. Although increased understanding of ecosystem behavior (through modeling and experimentation) may lower this uncertainty, there are no tools available to completely eliminate it.

The connection between thermodynamic concepts, ecological processes, and sustainability will also require more research and understanding to eliminate current uncertainty. There is no way of knowing which natural resources future generations will want or need, and this uncertainty may be unavoidable. Using a combination of the above indices from each of the disciplines may help overcome their individual shortcomings, thereby mitigating the unavoidable uncertainty of future preferences and possibilities.

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